REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
20-09-2015	Final Report	15-Sep-2012 - 14-Mar-2015

4. TITLE AND SUBTITLE
Final Report: Ultrafast laser system for producing on-demand single- and multi-photon quantum states

5a. CONTRACT NUMBER
W911NF-12-1-0562

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611103

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
61540-PH-RIP.3

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
Our final goal from this project is to realize on-demand single- and multi-photon sources that are key resources for quantum communication and computation technology; we have made significant progress toward that goal under this DURIP grant. In order to efficiently overcome the probabilistic generation of heralded photons via spontaneous parametric down-conversion (SPDC), and to realize an on-demand single-photon source, one can employ time-multiplexing. In this project, we have extended and implemented a time-multiplexed heralded single-photon source with a low loss and high speed optical storage system. We have observed that our preliminary implementation with

15. SUBJECT TERMS
single-photon source, multiplexing, quantum state synthesis

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Paul Kwiat
					19b. TELEPHONE NUMBER
					217-333-9116

Report Title

Final Report: Ultrafast laser system for producing on-demand single- and multi-photon quantum states

ABSTRACT

Our final goal from this project is to realize on-demand single- and multi-photon sources that are key resources for quantum communication and computation technology; we have made significant progress toward that goal under this DURIP grant. In order to efficiently overcome the probabilistic generation of heralded photons via spontaneous parametric down-conversion (SPDC), and to realize an on-demand single-photon source, one can employ time-multiplexing. In this project, we have extended and implemented a time-multiplexed heralded single-photon source with a low-loss and high-speed optical storage system. We have observed that our preliminary implementation with our current existing SPDC source outperforms all previous demonstrations of heralded single-photon sources. Moreover, we have made substantial progress in our efforts to optimize a SPDC photon-pair source for time multiplexing, accounting theoretical and practical aspects.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
09/19/2015	1.00	Kevin Zielnicki, Karina Garay-Palmett, Radhika Dirks, Alfred B. U'Ren, Paul G. Kwiat. Engineering of near-IR photon pairs to be factorable in space-time and entangled in polarization, Optics Express, (03 2015): 7894. doi: 10.1364/OE.23.007894

TOTAL: 1

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Toward a deterministic single-photon source based on temporally multiplexed parametric down-conversion, Fumihiro Kaneda, Hee Su Park, Kevin McCusker, Bradley Christensen, and Paul Kwiat, Single Photon Workshop 2013: Sources, Detectors, Components, and Applications
(Oak Ridge National Laboratory, October 15-18, 2013)

Multiplexed heralded single-photons toward a periodic and deterministic single-photon source, F. Kaneda, B. Christensen, J.J. Wang, H.-S. Park, K. McCusker, P. Kwiat, Single-Photon Workshop 2015 (Geneva, Switzerland, July 13 - 17, 2015)

Temporal Multiplexing toward Periodic and Deterministic Single-Photon Sources, Fumihiro Kaneda, Bradley Christensen, Jia Jun Wong, Heesu Park, Kevin McCusker, and Paul Kwiat, CLEO: QELS Fundamental Science 2015 (San Jose, California United States, May 10–15, 2015)

Temporal multiplexing toward a periodic and deterministic single photon source, F. Kaneda, B. G. Christensen, J. J. Wong, H. S. Park, K. T. McCusker and P. G. Kwiat, Workshop for Quantum Repeaters and Networks (Pacific Grove, California, May 15-17, 2015)

Temporal Multiplexing toward Deterministic Single Photon Generation,
Fumihiro Kaneda, Bradley Christensen, Jia Jun Wong, Hee-Su Park, Kevin McCusker, Paul Kwiat, DAMOP 2015 (Columbus, Ohio, June 8–12, 2015)

Number of Presentations: 5.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
09/19/2015	2.00	F. Kaneda, B. G. Christensen, J. J. Wong, K. T. McCusker, H. S. Park, P. G. Kwiat. A time-multiplexed heralded single-photon source, Optica (08 2015)
TOTAL:		**1**

Number of Manuscripts:

Books

Received	Book
TOTAL:	

Received	Book Chapter
TOTAL:	

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Fumihiro Kaneda	0.00
FTE Equivalent:	**0.00**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Paul Kwiat	0.00	No
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Please see Attachment

Technology Transfer

Final Report: DURIP equipment grant

Our final goal from this project is to realize on-demand single- and multi-photon sources that are key resources for quantum communication and computation technology; we have made significant progress toward that goal under this DURIP grant. In order to efficiently overcome the probabilistic generation of heralded photons via spontaneous parametric down-conversion (SPDC), and to realize an on-demand single-photon source, a time-multiplexed heralded single-photon source was proposed by Pittman, Jacobs, and Franson [1] in 2002. In this project, we have extended and implemented a time-multiplexed heralded single-photon source with a low-loss and high-speed optical storage system [2]. We have observed that our preliminary implementation with our current existing SPDC source outperforms all previous demonstrations of heralded single-photon sources. Moreover, we have made substantial progress in our efforts to optimize a SPDC photon-pair source for time multiplexing, accounting theoretical and practical aspects [3]. Details of our activities are described as below.

Time-Multiplexed Single-Photon Source

The basic idea of our scheme is shown in Fig. 1 (a,b). An optical-pulse train from a laser periodically pumps a nonlinear SPDC crystal with a period τ, and generates photon pairs (i.e., signal and idler photons) in one or more time slots. Each signal photon is sent to a single-photon detector (SPD) by which the photon detection "heralds" in which time slot the corresponding idler photon is present. By using an adjustable storage cavity with cavity length τ, any of the time slots heralded to contain an idler photon can be multiplexed onto a single output time window. Thus, the single-photon probability during the output time window is increased according to the number of pump pulses (time slots) N used for one cycle of the multiplexing; in a lossless system this probability can be made arbitrarily close to 1. Moreover, if N is large, the probability of generating unwanted multiple pairs in a given time slot can be made arbitrarily small, because the pump energy is "diluted" over the N time slots.

Using the equipment from this DURIP grant, we have implemented our proposed time-multiplexed heralded single-photon source (see Fig. 1 (c) [2]). Our existing SPDC source with a bismuth barium borate (BiBO) crystal produced degenerate signal and idler pairs with very high heralding efficiency (up to 75 - 81% [4]). We used a custom Brewster-angle polarizing beamsplitter (PBS1) and Pockels cell (PC), which achieve high-speed (< 5 ns) very low- loss (< 3 %) switching in an adjustable storage cavity. In addition, incorporating a low-loss (< 15%) optical delay line including a Herriott cell allows us to store/release a heralded single photon generated in the closest time slots to an output time window, thereby reducing the effective number of storage cycles and associated optical loss.

This preliminary implementation of a multiplexed source demonstrated largely enhanced single-photon probabilities: for high power pumping (mean photon number per time slot p = 0.35) we have observed a multiplexed single-photon probability P_{M1} = 38.6% (see blue dots in Fig. 1 (c)) by multiplexing N = 30, corresponding to ~6× enhancement in P_{M1} compared to the non-multiplexed source (P_{M1} = 6.6% for N = 1). With a low pump power (p ~0.07), we observed ~16× increase in the single-photon probability by multiplexing N = 30 (see green squares in Fig. 1 (d)). While the single-photon probability is greatly enhanced by the multiplexing, the second-order correlation function $g^{(2)}(\tau = 0)$ of the multiplexed source is as low as the non-multiplexed one (Fig. 1

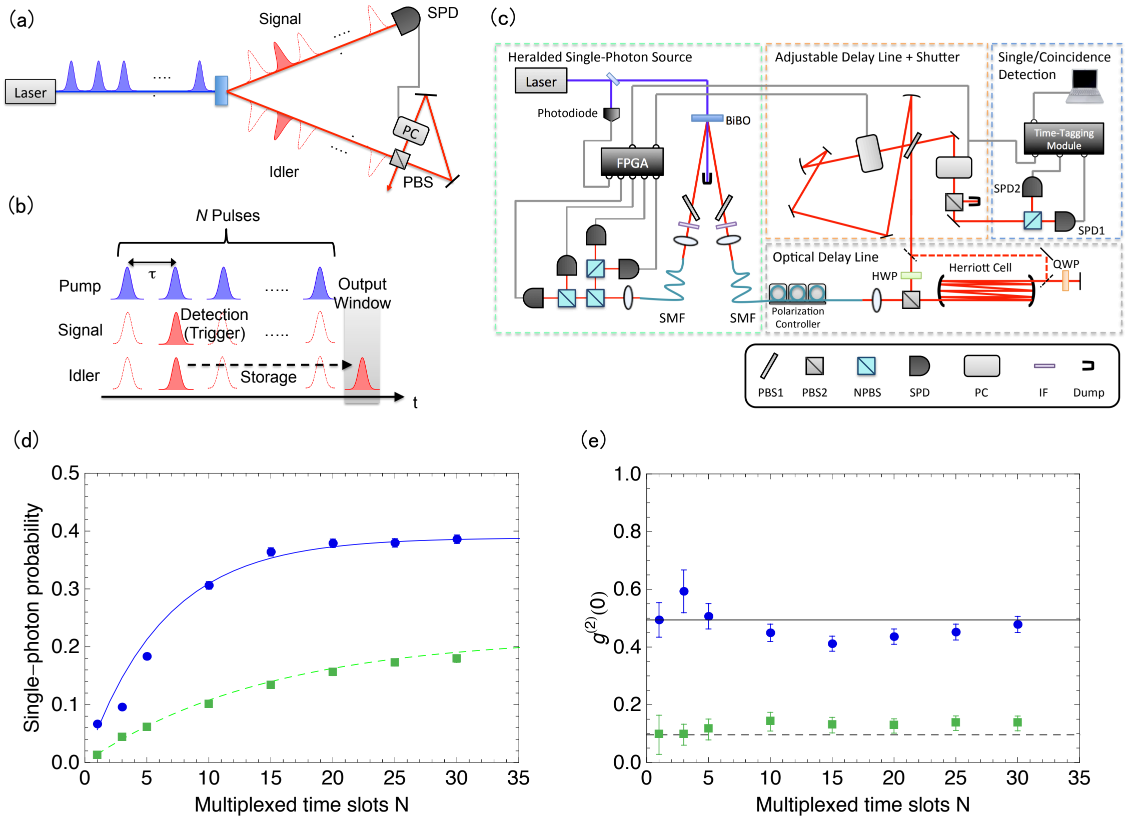


Fig. 1. (a) Simplified schematic diagram of a time-multiplexed heralded single-photon source. (b) Timing diagram of pump, signal, and idler photons. (c) Experimental setup of our prototype time-multiplexed source. (d) Single-photon probability and (e) the second-order correlation function $g^{(2)}(\tau = 0)$ versus number of multiplexed time slots N. Blue circles: $p = 0.35$. Green squares: $p = 0.07$. Solid and dashed lines in (d) show theoretical predictions for $p = 0.35$ and 0.07, accounting loss of experimental components. Solid and dashed lines in (e) indicate the values of $g^{(2)}(\tau = 0)$ measured without multiplexing ($N = 1$) for $p = 0.35$ and 0.07.

(e)): the ratio of the two- and single-photon probabilities P_{M2}/P_{M1} is independent of N. To our knowledge, these single-photon probabilities and enhancement factors are significantly higher than all previous demonstrations of heralded single photons. Moreover, we found that the low-loss high-speed optical switching technique developed in this experiment can be applied for "time demultiplexing" of photons: sequentially produced photons can be efficiently distributed to different channels of a photonic circuit for quantum computational applications such as linear optical quantum computing, quantum walks, and boson sampling.

Optimizing Heralded Single-Photon Source

Although our current time-multiplexed heralded single-photon source already outperforms all other heralded single-photon sources, many quantum information applications using a large number of quanta require even higher generation efficiencies (> 70%), in addition to high purity and indistinguishability to utilize multi-photon interference effects. In order to develop an optimized heralded single-photon source, we have made experimental and theoretical characterizations of photon pair sources. Our first attempt used SPDC from a non-collinear phase-matched beta-barium borate (BBO) crystal with group-velocity-matching (GVM) as a potential source of the high-quality heralded single photons. Although we measured a high spectral purity (> 80%) by various characterization techniques [3], theoretical calculations with the help of Alfred U'Ren in Universidad Nacional Autonoma de Mexico, subsequently revealed that it is difficult to achieve both high spectral purity and high heralding efficiency with this scheme: a tightly focused pump beam (beam waist ~30 μm) is necessary to obtain high spectral purity, but limits spatial mode correlation and heralding efficiency (~20%). Moreover, the short-pulse duration (Δt ~30 fs) of the heralded single-photon state would necessitate the storage cavity to have very precisely controlled chromatic dispersion and cavity length.

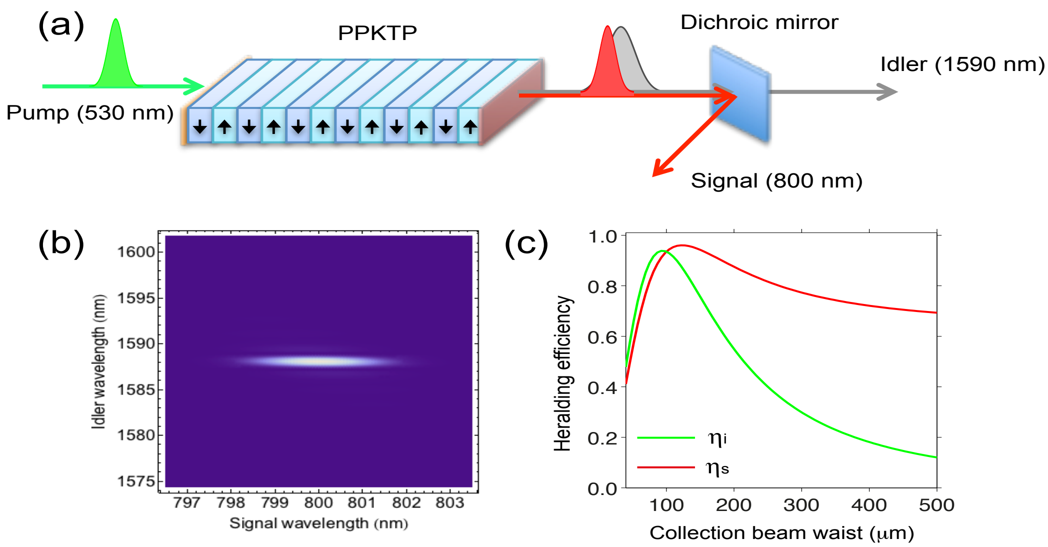


Fig. 2. (a) Schematic diagram of nondegenerate collinear SPDC with a PPKTP crystal. (b) Predicted joint spectral amplitude of signal and idler photons. (c) Predicted heralding efficiency as a function of collection beam waist of photons.

In order to improve the single-photon probability, to further suppress the multi-photon probability, and to obtain pure single-photon states, we designed a new photon pair source for heralded single photons (see Fig. 2 (a)). A 20-mm-long periodically poled potassium titanyl phosphate (PPKTP) crystal is pumped by a short pulse (Δt ~200 fs[1]) centered at 532 nm, and collinearly generates signal and idler photons at 800 nm and 1590 nm, respectively. In this configuration, pump and signal modes have the same group velocity (i.e., satisfying GVM), and frequency entanglement between signal and idler photons is nearly eliminated: the predicted two-photon joint spectral amplitude (Fig. 2 (b)) clearly shows the factorability of the two-photon state. We have measured single-photon purity up to 90%, much better than the 5% of the source used thus far in our time-multiplexed source (Fig. 1), and sufficient for our purposes.

Aside from satisfying group-velocity matching, the center wavelengths of the signal and idler photons are desirable for the following reasons: The photon centered at 800 nm

[1] Unfortunately, the pulses from our previous source laser were an order of magnitude too short for this source; also, our other existing pump sources had pulses that were in fact too *long* for the proposed source. The primary use of this DURIP Equipment fund was to acquire a new optimal pulsed pump laser.

is excellent for heralding the idler photon, since the wavelength is in the region of high sensitivities for commercial Si-APD (which has now demonstrated efficiencies above 85%) as well as Visible Light Photon Counters (VLPCs) [5].

The photon at 1590 nm is optimal for both storing in the cavity and maintaining high purity, because the group-velocity dispersion of the storage cavity (~0.0008 ps^2 per cycle) can be much lower than it would be in our current cavity, operating at a wavelength of 710 nm (corresponding to ~0.01 ps^2 per cycle)[2], and because the 1590-nm photon is generated with a very narrow bandwidth ($\Delta\lambda \sim 1$ nm, $\Delta t \sim 3$ ps), which makes it highly robust against chromatic dispersion in the storage cavity. Combined with a low-dispersion storage cavity, the photon's purity should be reduced less than 1% even for N = 100 cycles.

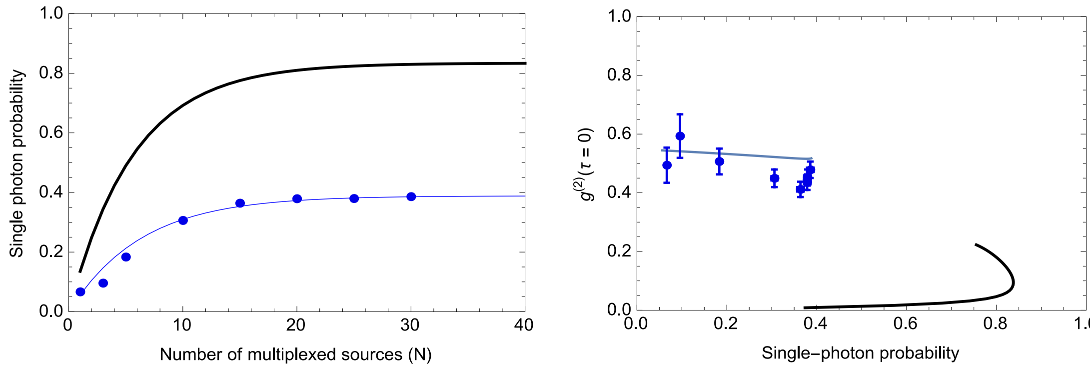


Fig. 3. Predicted performance of our proposed multiplexed heralded single-photon source. (a) Final single-photon probability vs N for single-pulse pair-production probability p = 0.18. (b) $g^{(2)}(0)$ vs single-photon probability parameterized by p. Blue lines and dots were obtained in our past experiment (see Fig. 1), while black lines are the predicted performance of our proposed source.

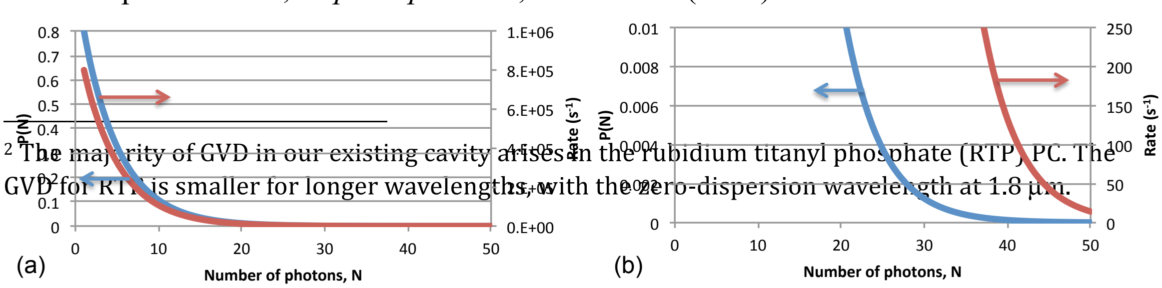
Incorporating all these improvements, we expect a final single-photon probability up to 83%, with a $g^{(2)}$ as low as 0.05 (see Fig. 3). Note that there is always a trade-off between these metrics, as indicated in Fig. 3 (b). Given an expected source efficiency of 0.8 and a source repetition rate of 1MHz (achieved by using a much faster PC driver than in our previous experiment), we can estimate the production rate of N-photon events $P(N) = 0.8^N$ x (1 MHz). As shown in Fig. 4, we can produce 8-photon events at 170,000/s (compared to ~0.5/s, the best result to date), even 50-photon events at 14/s (though these numbers do not include the detection efficiency for these photons).

References

[1] T. Pittman, B. Jacobs, and J. Franson, "Single photons on pseudodemand from stored parametric down-conversion," *Phys. Rev. A* **66**, 042303 (2002).

[2] F. Kaneda, B. G. Christensen, J. J. Wong, K. T. McCusker, H. S. Park, and P. G. Kwiat, "A time-multiplexed heralded single-photon source," *submitted to Optica*.

[3] K. Zielnicki, K. Garay-Palmett, R. Dirks, A. B. U'Ren, and P. G. Kwiat, "Engineering of near-IR photon pairs to be factorable in space-time and entangled in polarization.," *Opt. Express* **23**, 7894–7907 (2015).



[2] The majority of GVD in our existing cavity arises in the rubidium titanyl phosphate (RTP) PC. The GVD for RTP is smaller for longer wavelengths, with the zero-dispersion wavelength at 1.8 μm.

Fig. 4. (a) Predicted performance of our feasible source for N-photon state generations. (b) Enlarged version at low generation rates/probabilities.

[4] B. G. Christensen, K. T. McCusker, J. B. Altepeter, B. Calkins, T. Gerrits, A. E. Lita, A. Miller, L. K. Shalm, Y. Zhang, et al., “Detection-loophole-free test of quantum nonlocality, and applications,” *Phys. Rev. Lett.* **111**, 130406 (2013).

[5] J. Kim, K. S. McKay, P. G. Kwiat, K. Zielnicki, and E. J. Gansen, “Novel Semiconductor Single-Photon Detectors,” *in Experimental Methods in the Physical Sciences* **45**, 147–183 (2013).